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ELECTROSTATIC DECAY PRODUCTS IN
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7103 p-4DETECTABILITY OF ELECTROSTATIC DECAY PRODUCTS IN *ULYSSES* AND *GALILEO* OBSERVATIONS OF TYPE III SOLAR RADIO SOURCES

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ABSTRACT

Recent *in situ* *Ulysses* and *Galileo* observations of the source regions of type III solar radio bursts appear to show an absence of ion acoustic waves S produced by nonlinear Langmuir wave processes such as the electrostatic (ES) decay, in contradiction with earlier *ISEE 3* observations and analytic theory. This Letter resolves these apparent contradictions. Refined analyses of the maximum S -wave electric fields produced by ES decay and of the characteristics of the *Ulysses* Wave Form Analyzer (WFA) instrument show that the bursty S waves observed by *ISEE 3* should be essentially undetectable by the *Ulysses* WFA. It is also shown that the maximum S -wave levels predicted for the *Galileo* event are $\lesssim$ the instrumental noise level, thereby confirming an earlier suggestion. Thus, no contradictions exist between the *ISEE 3* and *Ulysses*/*Galileo* observations, and no evidence exists against ES decay in the published *Ulysses* and *Galileo* data. All available data are consistent with, or at worst not inconsistent with, the ES decay proceeding and being the dominant nonlinear process in type III bursts.

Subject headings: interplanetary medium — plasmas — solar wind — Sun: radio radiation — waves

1. INTRODUCTION

Over 30 years ago Ginzburg & Zheleznyakov (1958) suggested that nonlinear Langmuir wave processes are important in type III solar radio bursts. The processes considered since then include scattering off thermal ions (e.g., Ginzburg & Zheleznyakov 1958; Melrose 1980), three-wave coalescence and decay processes (e.g., Melrose 1982; Lin et al. 1986; Robinson, Willes, & Cairns 1993a; Thejappa et al. 1993a; Robinson, Cairns, & Willes 1994; Cairns & Robinson 1995) and modulational instabilities (e.g., Papadopoulos, Goldstein, & Smith 1974; Thejappa et al. 1993a, b). Questions remain as to the identities and roles of the important Langmuir wave processes. For instance, although scattering off thermal ions is well known to be ineffective, it is unresolved which three-wave and modulational (four-wave) processes are active and whether these processes quantitatively limit the Langmuir wave growth, allow persistence of the electron beam to distances ~ 1 AU, and generate the observed radiation. Indeed, comparisons of the recent stochastic growth theory with *ISEE 3* data (Robinson 1992; Robinson, Cairns, & Gurnett 1992, 1993b; Robinson et al. 1993a, 1994) imply that (linear) stochastic growth effects alone are responsible for limiting the growth of all but the largest amplitude Langmuir waves, for the observed wave clumping, and for the beam's persistence. These authors argue that specific three-wave processes are responsible for limiting the highest amplitude Langmuir waves and for generating the radiation.

The existence (or not) and frequencies of low-frequency ion acoustic waves produced in association with intense Langmuir waves, or fine structure in the Langmuir spectra and waveforms, constitute the simplest observational routes for testing which nonlinear processes are active in type III bursts. Lin et al. (1986) reported *ISEE 3* observations near 1 AU of such product waves. They found the wave frequencies to be commensurate with those expected (wavenumbers $\sim \omega_p/v_b$) for the electrostatic (ES) decay $L \rightarrow L' + S$ and the electromagnetic (EM) decay $L \rightarrow T(f_p) + S'$. Here L and L' de-

note primary and product Langmuir waves, respectively, S and S' are ion acoustic waves, $T(f_p)$ is a transverse EM wave with frequency close to the electron plasma frequency f_p , $\omega_p = 2\pi f_p$, and v_b is the beam speed. Lin et al. (1986) argued against modulational instabilities being relevant and found the wave frequencies to be most consistent with the EM decay (despite analytic theory definitely favoring the ES decay). However, a refined analysis of these same data (Cairns & Robinson 1995) found strong evidence that the ES decay produces the great majority of these waves. The data are also consistent with the EM decay proceeding (and producing radiation near f_p) when stimulated by the ES decay. In fact, three lines of evidence support the ES decay being the dominant nonlinear process in type III bursts: the frequencies and onset times of the observed low-frequency waves (Cairns & Robinson 1995), a cutoff in the probability distribution $P(E_L)$ at high L -wave electric fields E_L near the predicted threshold for ES decay (Robinson et al. 1993a, b), and the frequencies of beat waveforms observed by the *Galileo* spacecraft in a type III source region (Gurnett et al. 1993). The first two lines of evidence are derived from *ISEE 3* data.

At first sight, *Ulysses* observations from 1 to 4 AU appear totally at variance with this picture. Thejappa et al. (1993a) discussed three type III bursts with local radio emission and L waves but with no S -wave products above instrumental background. They calculated that the maximum S -wave fields predicted for ES decay should be well above the noise level and similar to the *ISEE 3* observations and thus argued that the absence of decay products implies that the ES and EM decays do not proceed, thereby contradicting the *ISEE 3* observations. Thejappa et al. (1993a, b) then argued that modulational instabilities produce, and the dominant radiation processes only involve, the localized Langmuir wave packets observed. However, no direct evidence for the modulational instability exists due to a lack of product waves.

Galileo observations of a type III burst near 1 AU (Gurnett et al. 1993) showed Langmuir waveforms with beats at frequencies consistent with ES decay, as predicted by Cairns &

Robinson (1992), but found no direct evidence for S -wave products. Gurnett et al. (1993) suggested that this might simply be a result of high noise levels but did not analyze the situation further.

This Letter investigates and resolves the apparent contradictions between the *ISEE 3* and *Ulysses/Galileo* data, addressing the very different interpretations adopted for the *ISEE 3* and *Ulysses* observations. Sections 2 and 3 present refined predictions for the maximum S -wave fields produced by ES decay for the *Ulysses* events, taking into account the characteristics of the relevant *Ulysses* wave instrument and using in situ plasma data. It is shown that S -wave bursts like those observed by *ISEE 3* should be essentially undetectable in the time-averaged *Ulysses* data. Analogous calculations in § 4 for the Gurnett et al. (1993) *Galileo* observations show that the maximum predicted S -wave fields for ES decay are less than or similar to the typical noise level. The key conclusion is that the apparent contradictions between the *ISEE 3* data and the *Ulysses* and *Galileo* data do not exist.

2. THEORETICAL FRAMEWORK

The ES decay $L \rightarrow L' + S$ proceeds fastest as a process that scatters a beam-driven L wave, with $k_L \sim \omega_p v_b / v_b^2$, into a backward going L' wave (with $k_{L'} \sim -k_L$) and a forward-going S wave with $k_S \sim 2k_L$ (e.g., Melrose 1982; Cairns 1987). Frequency and wavevector conservation and wave dispersion relations constrain the wave frequencies and wavevectors. A standard relation exists between the electric field energy density and the occupation number N_M of quanta in mode M .

$$\frac{1}{2} \epsilon_0 E_M^2 = \int \frac{d^3 k_M}{(2\pi)^3} \hbar \omega_M(k_M) R_M(k_M) N_M(k_M), \quad (1)$$

where $R_M(k_M)$ is the ratio of electric to total energy in the mode M . Considering conservation of the total number of quanta interacting and the volumes of wavevector phase space occupied by the participating waves, the maximum S -wave field is related semiquantitatively to the L -wave field by (Robinson et al. 1993a, eq. [47c])

$$E_S \lesssim E_L \left(\frac{8m_i}{m_e} \right)^{1/4} \left(\frac{V_s}{v_b} \right)^{3/2}. \quad (2)$$

Here V_s is the ion acoustic speed defined by $V_s^2 = k_B T_e (1 + 3T_i/T_e)/m_i$, and T_e and T_i are the electron and ion temperatures.

The limit of equation (2) is lower by a factor of $2 \times 2^{3/2}$ than the Thejappa et al. (1993a, p. 842) prediction. The factor of 2 refinement is caused by geometry: the solid angles $\Delta\Omega_S$ and $\Delta\Omega_L$ occupied by the S waves and primary L waves are related by $\Delta\Omega_S \approx \Delta\Omega_L$ (Robinson et al. 1993a) and not by the Thejappa et al. relation $\Delta\Omega_S = 4\Delta\Omega_L$. The factor of $2^{3/2}$ change arises from requiring conservation of the total number of quanta (Robinson et al. 1993a), rather than assuming conservation of occupation numbers.

3. ULYSSES ANALYSIS

Thejappa et al. (1993a) analyzed *Ulysses* observations of three type III bursts which exhibited local radio emission and Langmuir waves: one each in the periods 1300–1500 UT on 1990 December 11, 0630–0800 UT on 1991 February 22, and 1700–2000 UT on 1991 March 7. In each case $f_p \approx 10$ kHz. Two *Ulysses* detectors are relevant here (Stone et al. 1992): the Fast Envelope Sampler (FES) and the Wave Form Analyzer (WFA). For these bursts, the FES provided the L -wave

TABLE 1
Ulysses MEASUREMENTS OF T_e AND T_i

Event	Range of T_e (K)	Range of T_i (K)	T_e (K)	T_i (K)
Dec 11.....	$7.3\text{--}11 \times 10^4$	$2.8\text{--}6.4 \times 10^4$	1.0×10^5	4.5×10^4
Feb 22.....	$7.4\text{--}7.9 \times 10^4$	$1.0\text{--}1.7 \times 10^4$	7.6×10^4	1.3×10^4
Mar 7.....	$4.0\text{--}4.9 \times 10^4$	$0.7\text{--}1.9 \times 10^4$	4.5×10^4	1.3×10^4

envelope fields every 1 ms in blocks 1024 samples long in a 6–60 kHz bandwidth (the detector time constant is less than 1 ms). Owing to telemetry restrictions, only the FES period with the highest peak field is retained and reported approximately every half-hour. Detailed operation of the WFA is described below; for now, we note that the WFA covers the frequency range for ES decay product waves and provides outputs once every DPU cycle (64 or 128 s, depending on the telemetry rate) with a large amount of instrumental dead time. Since both the L and S waves observed by *ISEE 3* (Lin et al. 1986) and the L waves observed by *Ulysses* (Kellogg et al. 1992; Thejappa et al. 1993a) are extremely spiky, the slow sampling rate and large dead time of the WFA instrument makes it very difficult to detect ES decay products, as we show below.

Two further refinements to the previous analysis are to use in situ *Ulysses* measurements for T_e and T_i in equation (2) rather than nominal values, and to consider time variations in v_b (e.g., Lin et al. 1981, 1986) rather than a single nominal value. In fact, the measured T_e and T_i are substantially lower than the Thejappa et al. (1993a) assumed values $T_e = 2 \times 10^5$ K and $T_i = 4 \times 10^4$ K. The effect of this underestimation can be seen by rearranging equation (2) as

$$E_S \lesssim E_{S\max} = E_L 2^{3/2} \left(\frac{m_e}{m_i} \right)^{1/4} \left(\frac{V_e}{v_b} \right)^{3/2} (1 + 3T_i/T_e)^{3/4}, \quad (3)$$

where $V_e = (k_B T_e/m_e)^{1/2}$ is the electron thermal speed. Reducing T_e or the ratio T_i/T_e therefore reduces the maximum S -wave field $E_{S\max}$ predicted for ES decay products.

Table 1 summarizes *Ulysses* data for T_e and T_i from the SWOOPS instrument for the three events (J. L. Phillips 1995, private communication; see Phillips et al. 1993), giving observed ranges and typical values of T_e and T_i . The quoted T_e values are those for the “core” component of the solar wind electron distribution, since V_s is small compared with the core and halo thermal speeds. The quoted T_i are averages of the maximum and minimum values measured. Since *Ulysses* does not measure the beam velocity, we consider a range $v_b = 3.5\text{--}10 \times 10^7$ m s^{−1} based on *ISEE 3* data (Lin et al. 1981, 1986; Cairns & Robinson 1995).

The maximum ratios of S -wave to L -wave fields calculated from equation (3), based on Table 1's typical T_e , T_i values and the range of v_b , are given in Table 2's third column. These ratios are then multiplied by the maximum FES L -wave fields (col. [4]) to give $E_{S\max}$. The quoted FES fields correspond to the broad wave packets seen, not the superposed 1 ms spikes sometimes seen; the 1 ms spikes have spatial scales ~ 10 times too small to excite ES decay products in the range 100–300 Hz range observed by *ISEE 3*. Column (5) gives the value of $E_{S\max}$ observable by an ideal FES-like detector. As described more below, instrumental limitations and the intrinsic burstiness of the L and S waves limit the detectability of these S -wave fields. The final column contains the noise level in the WFA 112 Hz “channel” for each event, obtained from the Thejappa et al. (1993a) figures as the square root of the background spectral

TABLE 2
MAXIMUM PREDICTED *S*-WAVE LEVELS AND THE *Ulysses* INSTRUMENTAL NOISE LEVELS

Event (1)	v_b (ms^{-1}) (2)	Ratio E_S/E_L (3)	FES E_L (mV m^{-1}) (4)	Ideal E_S ($\mu\text{V m}^{-1}$) (5)	Noise ($\mu\text{V m}^{-1}$) (6)
Dec 11.....	10×10^7	1.1×10^{-3}	3.0	3.4	2.8
	3.5×10^7	5.4×10^{-3}	3.0	16	2.8
Feb 22.....	10×10^7	6.5×10^{-4}	2.5	1.6	1.0
	3.5×10^7	3.1×10^{-3}	2.5	7.9	1.0
Mar 7.....	10×10^7	5.2×10^{-4}	5.0	2.6	1.2
	3.5×10^7	2.5×10^{-3}	5.0	12	1.2

density times the channel bandwidth. Table 2 shows that $E_{S\text{max}} \approx 16 \mu\text{V m}^{-1}$, less than 2–10 times the noise background. These fields are smaller than the Thejappa et al. (1993a) quoted upper limit of $32 \mu\text{V m}^{-1}$ owing to the use of measured plasma parameters and the refined prediction in equation (3).

Before detailed consideration of the WFA's characteristics (Stone et al. 1992; P. J. Kellogg & R. J. MacDowall 1995, private communications), it might appear that ES decay products should be easily detectable. This is, however, not the case. The WFA's input is a bandpass-limited signal sampled at 1792 Hz. The WFA measures a spectrum for each octant of spacecraft spin (spin period ~ 12 s), with spectral densities calculated at specific frequencies (448, 224, 149, 112 Hz, etc.) using windowed digital fourier transforms on four cycle lengths (16 samples) of the field time series (appropriately time-averaged). The peak spectrum for each octant is constructed using the maximum spectral density at each "channel" frequency every DPU cycle (64 or 128 s). Average spectra are constructed for each "quadrant" of spacecraft spin by averaging over opposing octants and then over the spin periods in each DPU cycle. For these bursts, the WFA reported four time-averaged quadrant spectra and eight peak octant spectra every 64 s. The analysis proceeds in four stages:

1. Using only a four-cycle time interval every 1.5 s for calculating the spectral density at each frequency means that the instrument has substantial dead time at high frequencies (P. J. Kellogg 1995, private communication). For instance, the dead time at 112 Hz is $(1.5 - 4/112)$ s, or $\sim 98\%$ of the time between spectra; the percentage of dead time decreases at the lower frequencies. The probability P_{on} of the WFA sampling at a given time is thus $\sim 2\%$ at 112 Hz or above, as a result of the long instrumental dead time.
2. Analysis of the Cairns & Robinson (1995) detailed *ISEE 3* *L*- and *S*-wave data indicates that the probability, P_{burst} , of an *S*-wave burst produced by ES decay occurring at a given time ranges from $\sim 1\%$ to 3% at 1 AU.
3. The probability of the WFA being on and sampling an *S*-wave spike is then the product $P_{\text{on}}P_{\text{burst}} \sim 0.02\% - 0.06\%$ at 1 AU. Therefore the WFA needs to process 2000–5000 spectra on average in order to sample one *S*-wave burst. Since the WFA calculates 40 octant spectra every 64 s, this number of spectra corresponds to an event duration of 50–130 minutes. That is, the WFA is predicted to sample only about one *S*-wave burst every 1–2 hr; this corresponds to approximately one *S*-wave burst for each of Thejappa et al.'s (1993a) events.
4. Thejappa et al. (1993a) present WFA data from the time- and quadrant-averaged spectra. Consider the 40 octant spectra used to construct this 64 s average and suppose that

at some frequency n spectra are enhanced by an average factor α above the true noise level A_i . Then the average is

$$A_{\text{app}} = A_i \left[1 + \frac{n(\alpha - 1)}{40} \right]. \quad (4)$$

Table 2's last two columns imply that $\alpha \approx 10$ for ES decay products. For $n = 1$ (justified by point 3 above), then $A_{\text{app}} \approx 1.1A_i$ for $\alpha = 5$, and $A_{\text{app}} \approx 1.2A_i$ for $\alpha = 10$. Thus, even if an ES decay spike occurs in one 64 s period it will increase the apparent noise level by $\lesssim 20\%$. Enhancements of this magnitude are essentially undetectable in Thejappa et al.'s (1993a) data owing to the presence of multiple, fairly periodic variations in the spacecraft's average noise level of similar or larger size.

In summary, the mode of operation of the *Ulysses* WFA instrument and the rarity and burstiness of the ES decay products observed by *ISEE 3* lead to the prediction that *S*-wave signals should be extremely rare in the *Ulysses* WFA data and essentially unobservable in the average WFA output. Thejappa et al.'s (1993a) result of an apparent absence of *S*-wave signals in the WFA data is therefore theoretically expected. The best chance of observing ES decay products with *Ulysses* is in the peak WFA spectra. Even in the peak data, however, the maximum *S*-wave fields predicted are only ~ 2 – 10 times the average noise level, with one *S*-wave detection expected every 1–2 hr. An extremely low likelihood exists then of a successful detection, consistent with Thejappa et al. (1993a) not identifying *S*-wave events in the peak data. The published *Ulysses* data therefore provide no evidence for or against the ES decay proceeding, there is no contradiction between the *Ulysses* and *ISEE 3* observations, and there is also no necessity (based on these data) to appeal to modulational instabilities to limit *L*-wave growth and reduce the beam's energy losses. The present *Ulysses* data are therefore not inconsistent with theories, based on *ISEE 3* data that rely heavily on ES decay (e.g., Cairns & Robinson 1992, 1995; Robinson et al. 1993a, b, 1994).

4. GALILEO ANALYSIS

Gurnett et al. (1993) reported Galileo observations at 0.98 AU of the *L* waves, radio emission, and electrons of a type III burst on 1990 December 10. Beats in the Langmuir waveforms had frequencies consistent with ES decay, as predicted by Cairns & Robinson (1992). However, no *S*-wave products of ES decay were observed directly; Gurnett et al. (1993) suggested this was the result of high instrumental noise levels. This suggestion can be evaluated similarly to the *Ulysses* observations. Gurnett et al. (1993) presented wideband re-

TABLE 3
MAXIMUM PREDICTED S-WAVE LEVELS AND THE *Galileo* INSTRUMENTAL NOISE LEVELS

v_b (ms^{-1}) (1)	Ratio E_S/E_L (2)	Wide-band E_L (mV m^{-1}) (3)	Ideal E_S ($\mu\text{V m}^{-1}$) (4)	Channel E_L (mV m^{-1}) (5)	Max E_S ($\mu\text{V m}^{-1}$) (6)	100 Hz ($\mu\text{V m}^{-1}$) (7)	316 Hz ($\mu\text{V m}^{-1}$) (8)
10×10^7	1.3×10^{-3}	1.7	2.2	0.5	0.6	4.5	2.3
3.5×10^7	6.1×10^{-3}	1.7	10	0.5	3.1	4.5	2.3

ceiver and spectrum (channel) analyzer data for the L waves, but only the channel analyzer sampled the frequency range predicted for ES decay products.

Two important effects influence predictions for the maximum S -wave fields observable by *Galileo*. First, comparison of Gurnett et al.'s (1993) wide-band and channel L -wave data (their Figs. 6 and 2, respectively) implies that the 50 ms detector time constant and slow sampling rate (once every 37.3 s) for the channel fields cause them to be underestimated by a factor ~ 3.4 ($= 1.7 \text{ mV m}^{-1}/0.5 \text{ mV m}^{-1}$) compared with the maximum fields seen by the wide-band receiver. The S -wave fields are sampled using the low-frequency channels, also with time constants ~ 50 ms, thereby being subject to the same underestimation when compared with predictions based on the wide-band L -wave fields. The maximum observable S -wave field predicted, $E_{S\text{max,obs}}$, is therefore reduced by the same factor of 3.4 compared with a prediction that does not take into account time constant and sampling rate effects.

Second, Gurnett et al. (1993) used a nominal $T_e = 1.3 \times 10^5$ K as a result of the *Galileo* thermal plasma instrument being switched off. Taking other nominal parameters $T_e/T_i = 3$ and $v_b = 3\text{--}10 \times 10^7 \text{ m s}^{-1}$ and including the underestimation factor, the predictions for $E_{S\text{max,obs}}$ are given in Table 3's column (6): $E_{S\text{max,obs}} \sim 1\text{--}3 \mu\text{V m}^{-1}$. (Col. [4] shows the ideal $E_{S\text{max}}$, i.e., without the underestimation factor.)

The instrumental background fields were investigated using averages of four spectrum analyzer channels (with intrinsic bandwidths ~ 5 Hz) centered at 100 Hz and 316 Hz, with time resolution of 32 s provided by D. A. Gurnett & L. J. Granroth (1995, private communications). For the period 0800–0830 UT, before the L -waves started, the typical 100 Hz fields were $\sim 4.5 \mu\text{V m}^{-1}$ with minimum and maximum fields of 2.8 and $24 \mu\text{V m}^{-1}$. The typical 100 Hz fields remained at levels $\sim 5 \mu\text{V m}^{-1}$ for the event period 0830–1000 UT, while the minimum and maximum fields were 1.5 and $65 \mu\text{V m}^{-1}$. At 316 Hz the fields showed little variation over the entire period 0800–1000 UT: the typical field remained $\sim 2.3 \mu\text{V m}^{-1}$, and the minimum and maximum fields observed were 1.5 and $4.0 \mu\text{V m}^{-1}$. Table 3 makes it clear that $E_{S\text{max,obs}}$ is predicted to be below or similar to the typical noise level and only slightly above the lowest channel fields observed. We therefore confirm the Gurnett et al. (1993) suggestion that sensitivity effects

should prevent reliable detection of ES decay products for this event. (Also, *Galileo*'s low sampling rate implies that it should sample S -waves ~ 10 times less often as ISEE 3.)

5. CONCLUSIONS

The detectability of ion acoustic products of the ES decay $L \rightarrow L' + S$ has been examined in detail for recent *Ulysses* and *Galileo* observations of type III burst source regions. In both cases, the nonobservation of ES decay products has been explained: waves similar to those observed by ISEE 3 (Lin et al. 1986; Cairns & Robinson 1995) could be present but would be essentially undetectable using the *Ulysses* or *Galileo* plasma wave detectors. For the *Ulysses* events discussed by Thejappa et al. (1993a) this nondetectability is due to (1) the maximum S -wave fields being less than a factor of 10 above the background, (2) the use of quadrant- and time-averaged WFA data, which should limit the effect of the maximum S -wave burst to raising the nominal noise level by $\lesssim 20\%$ (thereby rendering bursts essentially undetectable), and (3) the large instrumental dead time of the WFA and the burstiness of the (ISEE 3) S waves, implying that the WFA should very rarely detect an S -wave burst (only one every 1–2 hr on average). The lack of ES decay products in the *Galileo* data is due to the predicted maximum S -wave fields being less than or of order the typical noise level, thereby confirming Gurnett et al.'s (1993) suggestion. The available *Ulysses* WFA and *Galileo* channel data thus provide no evidence for or against the ES decay proceeding, there is no contradiction between the ISEE 3 observations and the *Ulysses* and *Galileo* observations, and these data do not argue that modulational instabilities limit the Langmuir wave growth (in the apparent absence of ES decay) for the *Ulysses* and *Galileo* events. Indeed, now all the available data are consistent with, or at worst not inconsistent with, the ES decay proceeding and being the dominant non-linear process in type III bursts, as predicted by analytic theory.

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REFERENCES

- Cairns, I. H. 1987, *J. Plasma Phys.*, **38**, 179
 Cairns, I. H., & Robinson, P. A. 1992, *Geophys. Res. Lett.*, **22**, 2187
 ———. 1995, *ApJ*, in press
 Ginzburg, V. L., & Zheleznyakov, V. V. 1958, *Soviet Astron.—AJ*, **2**, 653
 Gurnett, D. A., Hospodarsky, G. B., Kurth, W. S., Williams, D. J., & Bolton, S. J. 1993, *J. Geophys. Res.*, **98**, 5631
 Kellogg, P. J., Goetz, K., Howard, R. L., & Monson, S. J. 1992, *Geophys. Res. Lett.*, **19**, 1303
 Lin, R. P., Levedahl, W. K., Lotko, W., Gurnett, D. A., & Scarf, F. L. 1986, *ApJ*, **308**, 954
 Melrose, D. B. 1980, *Plasma Astrophysics*, Vols. I and II (New York: Gordon & Breach)
 ———. 1982, *Sol. Phys.*, **79**, 173
 Papadopoulos, K. D., Goldstein, M. L., & Smith, R. A. 1974, *ApJ*, **190**, 175
 Phillips, J. L., Bame, S. J., Gosling, J. T., McComas, D. J., Goldstein, B. E., & Balogh, A. 1993, *Adv. Space Res.*, **13**(6), 47
 Robinson, P. A. 1992, *Sol. Phys.*, **139**, 147
 Robinson, P. A., Cairns, I. H., & Gurnett, D. A. 1992, *ApJ*, **387**, L101
 ———. 1993b, *ApJ*, **407**, 790
 Robinson, P. A., Cairns, I. H., & Willes, A. 1994, *ApJ*, **422**, 870
 Robinson, P. A., Willes, A., & Cairns, I. H. 1993a, *ApJ*, **408**, 720
 Stone, R. G., et al. 1992, *A&AS*, **92**, 291
 Thejappa, G., Lengyel-Frey, D., Stone, R. G., & Goldstein, M. L. 1993a, *ApJ*, **416**, 831
 Thejappa, G., Lengyel-Frey, D., Stone, R. G., & Goldstein, M. L. 1993b, *Nature*, submitted